# Radiation Transport Methods for Space Applications

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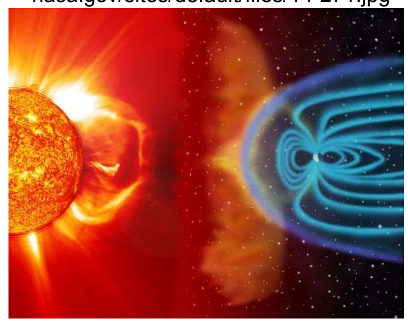
# Outline

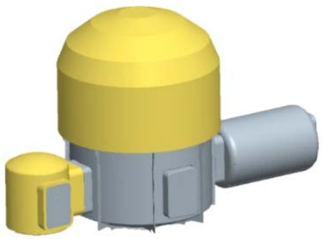
- Space radiation analysis procedures
- Description of radiation interactions with matter
  - Emphasis on physical interactions of greatest importance in human space applications
- Deterministic and Monte Carlo methods
- Beams vs. space radiation
- SPE and GCR exposure vs. depth

2009 NSRSS

# Exposure Analysis Overview

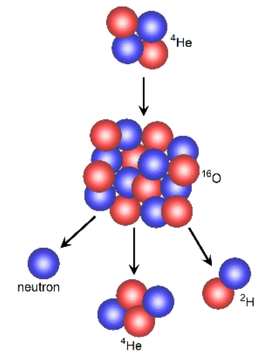
nasa.gov/sites/default/files/14-271.jpg





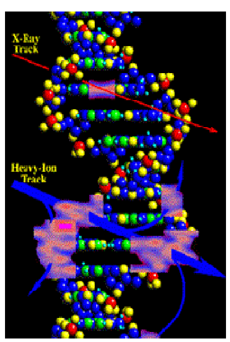
Shielding models

Environment models



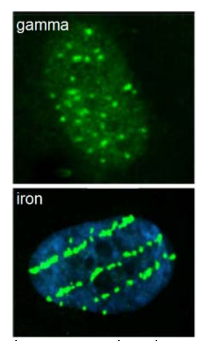

Physics models

Radiation transport models




nasa.gov/centers/johnson/slsd/about/divisions/hacd/hrp/about-space-radiation.html

Exposure & Biological response




humanresearchroadmap.nasa.gov/evidence/reports/Carcinogenesis.pdf

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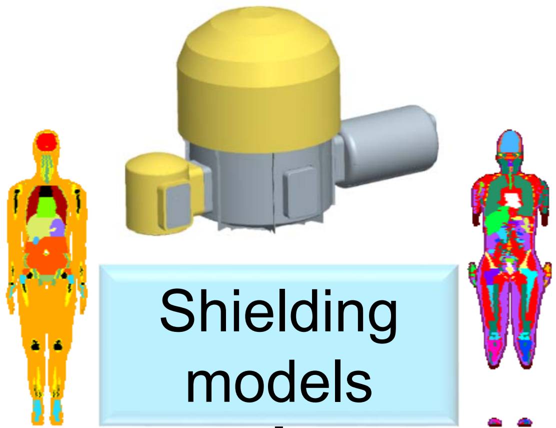

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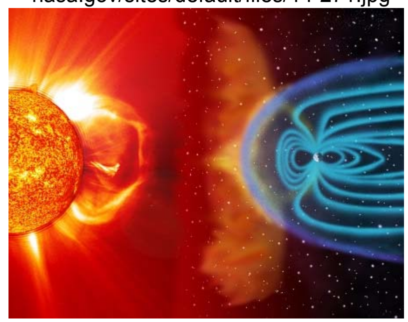

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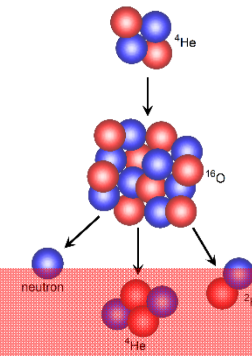


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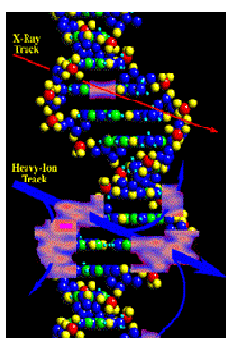


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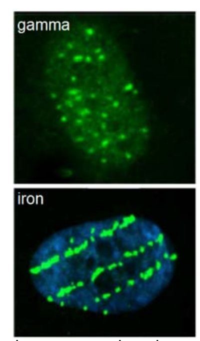


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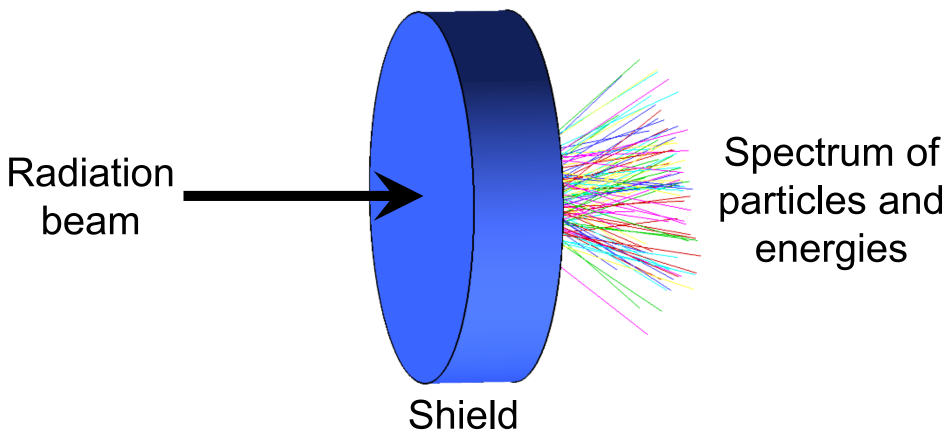
# Terminology

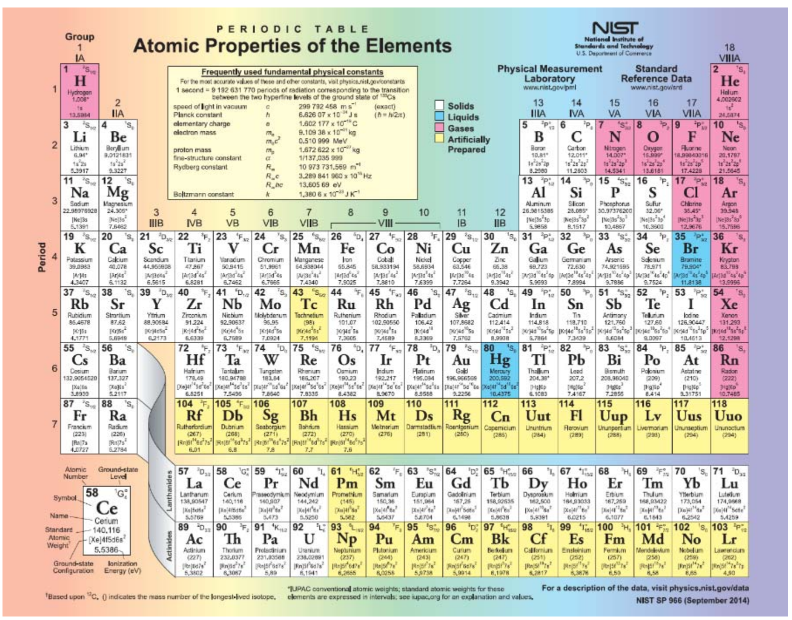
- Flux
  - The main physical quantity that goes into and comes out of radiation transport codes
  - Most, if not all, of the radiation protection quantities are determined from the flux (e.g. dose, dose equivalent, tissue damage, cancer risk)
  - The units of flux are generally: particles/($cm^2$-MeV/n-time)
  - Can be thought of as counting the number of particles with a given energy (MeV/n units) crossing a detector area ($cm^2$ units) in a given time interval (time units)
- Cross section
  - Quantifies the probability of a specific physical interaction occurring at a microscopic level
  - Models are used to compute cross sections as input into radiation transport codes
  - For example: The probability of a proton at 1 GeV striking an aluminum target and producing a neutron with a given energy and direction

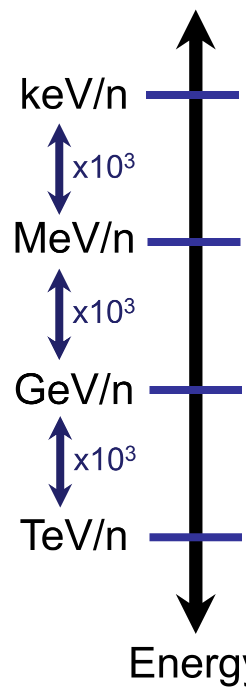


# Background

- The term “space radiation applications” is going to be used broadly here to refer to the following areas
  - Radiobiology studies focused on endpoints of interest to human spaceflight
  - Engineering studies focused on shield design and optimization for human space flight

- Relevant energies and particles in space radiation applications
  - Energies ranging from keV/n up to TeV/n
  - Particles include heavy ions, neutrons, electrons, positrons, gammas, and some mesons




- Stopped by thinnest shielding (skin)
- Important energy region for delta rays and some target fragments

- Able to penetrate to some tissue sites
- Important energy region for local energy deposition in tissue and Solar Particle Events

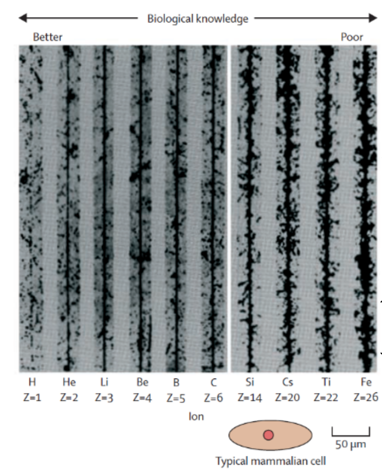
- Able to penetrate spacecraft shielding and tissue
- Important energy region for Galactic Cosmic Rays

- Able to penetrate just about everything, even through Earth atmosphere (1000 g/cm$^2$)

# Physical Interactions

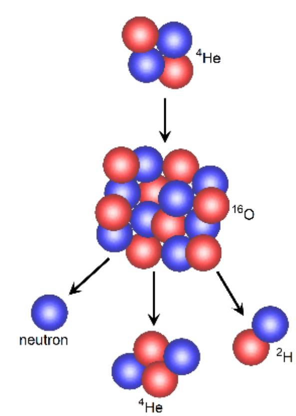
- As radiation passes through bulk materials (shielding and/or tissue), physical interactions modify the original particles and may result in the production of secondary particles
  - In the present context, assume that charged particles interacting with matter are fully ionized

- Atomic interactions
  - Interaction between positively charged ions and orbital electrons of target nuclei
  - Main physical mechanism for energy deposition
  - ~$10^6$ atomic interactions occur in a cm of matter
  - Production of delta rays along the ion track (track structure)




McDonald, NASA SP 71 (1965)

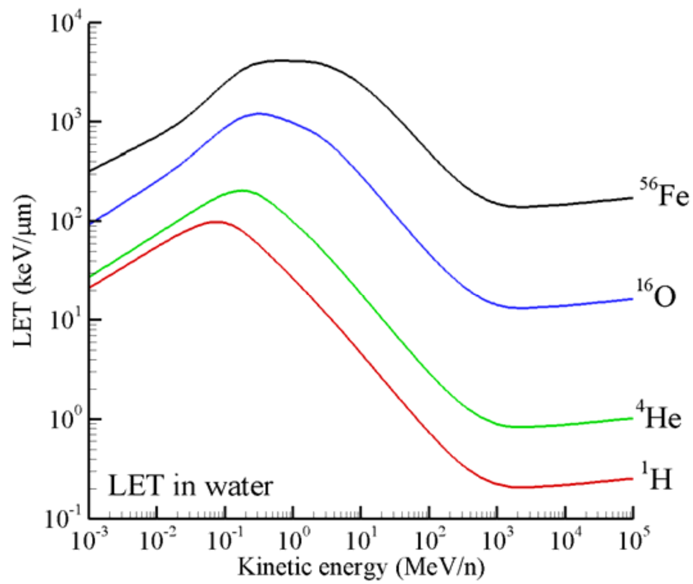
- Nuclear interactions
  - Interaction between incoming radiation and target nuclei
  - May be separated by a fraction to many cm of matter
  - Nuclear elastic: think of classical "pool-ball" collision
  - Nuclear inelastic: think of "pool-balls" breaking apart into pieces and some new pieces possibly being created
  - Nuclear interactions are very important in describing how space radiation is modified as it passes through shielding and tissue



# Atomic Interactions

- Many (~$10^6$) atomic interactions occur in a cm of matter, allowing them to be viewed as a "continuous" process instead of "discrete" interaction
  - In comparison, nuclear collisions are viewed as "discrete" processes

- The representation of atomic interactions as a "continuous" process is referred to as the continuous slowing down approximation (CSDA)
  - The atomic interaction cross sections are modified and expressed as the ion linear energy transfer (LET) or stopping power (sometimes denoted as S(E))
  - LET is defined as the average energy lost per unit path length (-dE/dx)
  - The terms stopping power and LET are used interchangeably here

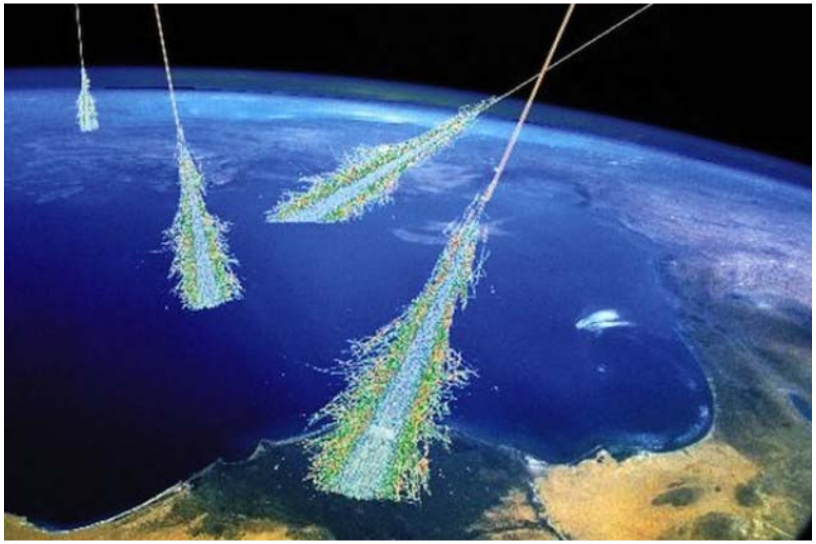


# Nuclear Interactions

- Nuclear interactions may be broadly separated into two main categories

- Elastic collisions
  - Classical “pool-ball” type collision in which the primary particle may transfer some energy to the target and/or change direction, but no particles are lost and no new particles are produced
  - Neutrons have no charge and are unaffected by orbital target electrons; elastic collisions are the primary interaction for describing neutron transport through materials

- Inelastic collisions
  - Interaction in which new particles are produced from the projectile and/or target
  - Produced particles (secondaries) are generated with a range of energies and directions
  - Secondary particles must also be accounted for in transport and could produce more particles (cascade)



Artist depiction of cosmic ray induced atmospheric cascade. [Simon Swordy (U. Chicago), NASA]

# Nuclear Interactions

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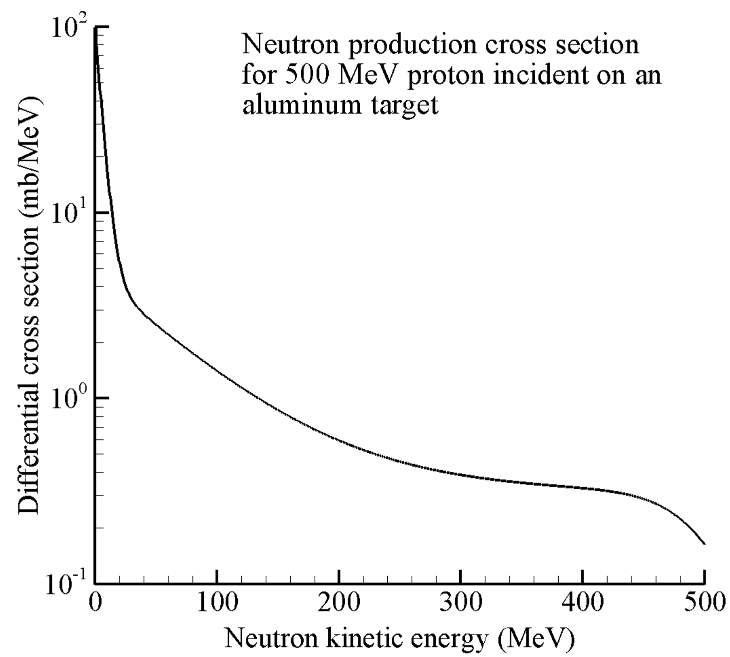


# Particle Transport Methods

## Simplified description of particle transport methods

- Mainly explanation through examples
- Emphasis on space applications

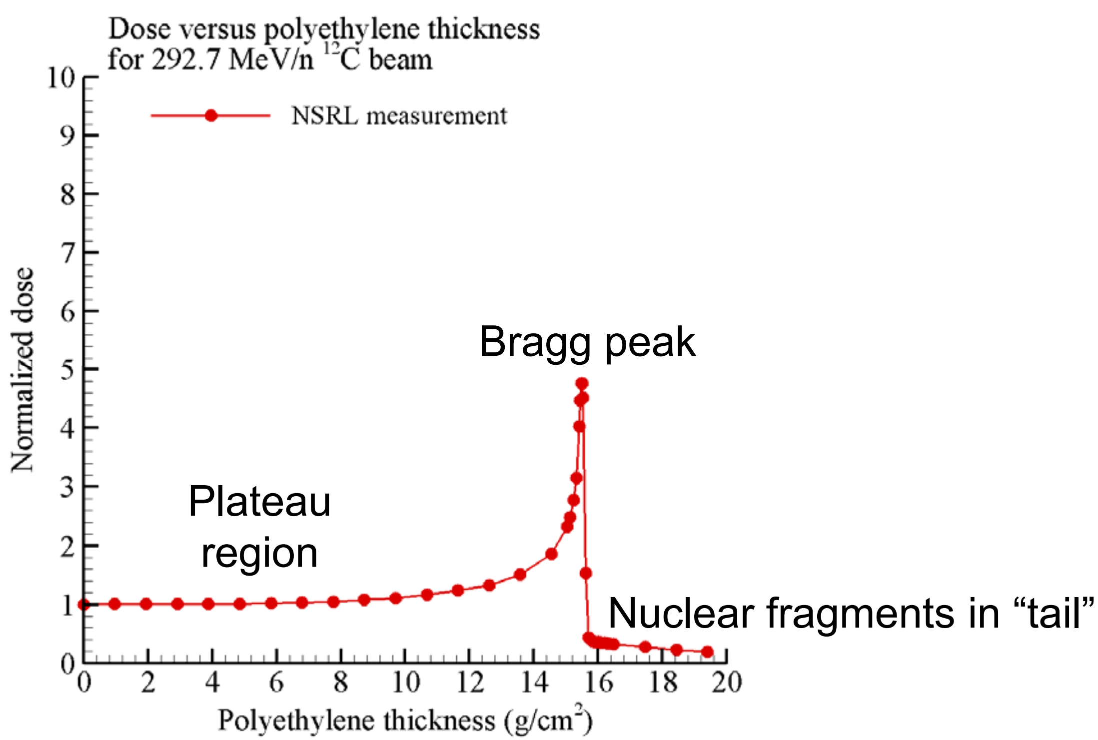
## Outline:

- Simplified analytical approach for low energy ion beam transport
- Deterministic methods for space radiation transport
- Monte Carlo (stochastic) methods for particle transport

# Low Energy Beam Transport

- Low energy (E < 500 MeV/n) proton and carbon beams are sometimes use to treat certain types of cancer
  - Main advantage is that atomic interactions precisely specify where charged particles stop in matter, leading to a localized energy deposition site often referred to as the Bragg peak

- For these low energies, certain physical approximations can be made that allow simplified analytical transport procedures to be developed



# Low Energy Beam Transport

- First order approximation for charged particles is to include CSDA and neglect nuclear interactions completely
  - Note: $\varphi_j(x,E)$ is the flux of type "j" particles at depth x with kinetic energy E. The "boundary condition" for this equation is a mono-energetic ion beam with unit intensity.

Particle LET as a function of kinetic energy

$$\frac{\partial}{\partial x}\phi_j(x,E) - \frac{\partial}{\partial E}[\phi_j(x,E)\tilde{S}_j(E)] = 0$$

Drift operator: Rate of change of flux with respect to depth in material

CSDA term: Energy loss due to interaction with target electrons

Simplified equation can be solved analytically

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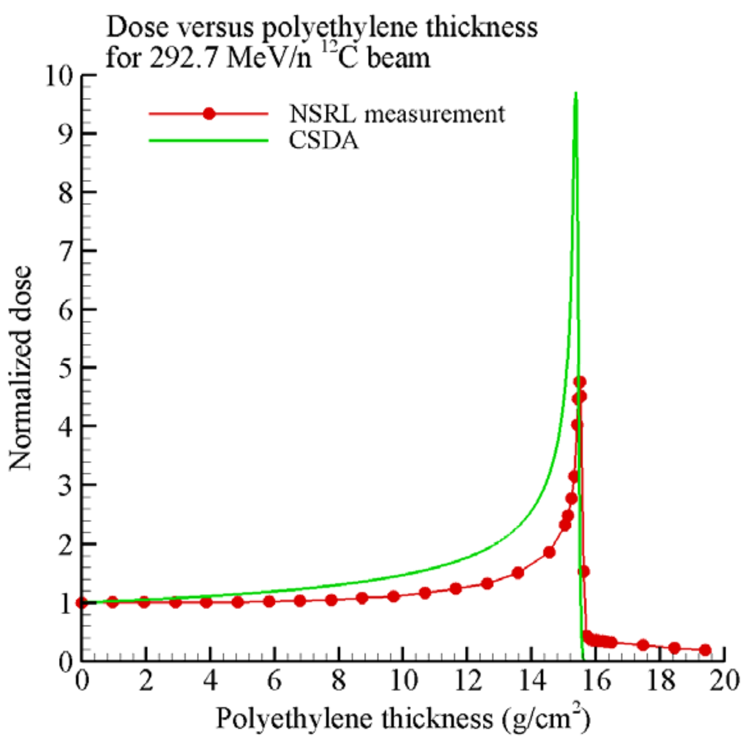


- Location of Bragg peak (depth) is reasonably accurate
- Over-estimating dose-depth curve in plateau region
- Not capturing “tail” of curve associated with nuclear fragments

# Low Energy Beam Transport

- Correction to simple CSDA can be obtained by including attenuation (loss) term associated with nuclear interactions

$$\frac{\partial}{\partial x}\phi_j(x,E) - \frac{\partial}{\partial E}\left[\phi_j(x,E)\tilde{S}_j(E)\right] + \sigma_j(E)\phi_j(x,E) = 0$$

Drift operator: Rate of change of flux with respect to depth in material

CSDA term: Energy loss due to interaction with target electrons

Nuclear attenuation term: Particles that suffer a nuclear collision are considered “lost” or “absorbed” by the medium

Simplified equation can be solved analytically

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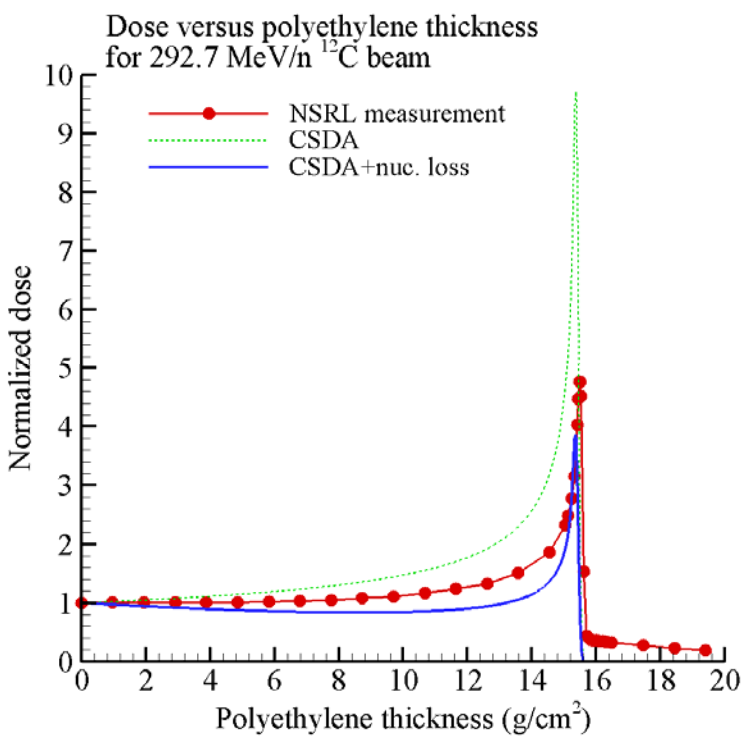


- Now under-estimating dose-depth curve in plateau region, although improvements can be seen

- Not capturing “tail” of curve associated with nuclear fragments

# Low Energy Beam Transport

- Another correction is to include production of secondary particles from nuclear collisions (1D Boltzmann transport equation)

$$\frac{\partial}{\partial x}\phi_j(x,E) - \frac{\partial}{\partial E}[\phi_j(x,E)\tilde{S}_j(E)] + \sigma_j(E)\phi_j(x,E) = \sum_k \int \sigma_{k\rightarrow j}(E,E')\phi_k(x,E')\,dE'$$

Drift operator: Rate of change of flux with respect to depth in material

CSDA term: Energy loss due to interaction with target electrons

Nuclear attenuation term: Particles that suffer a nuclear collision are considered “lost” or “absorbed” by the medium

Nuclear production term: All processes by which a type “k” particle might produce a type “j” particle at a given energy

- 1D Boltzmann transport equation includes CSDA and nuclear attenuation and production
- Requires combination of analytical and computational methods to solve
- 3D effects and higher order correction terms (straggling) not accounted for that are sometimes important in beam comparisons
- Basis for space radiation transport code HZETRN

# Low Energy Beam Transport

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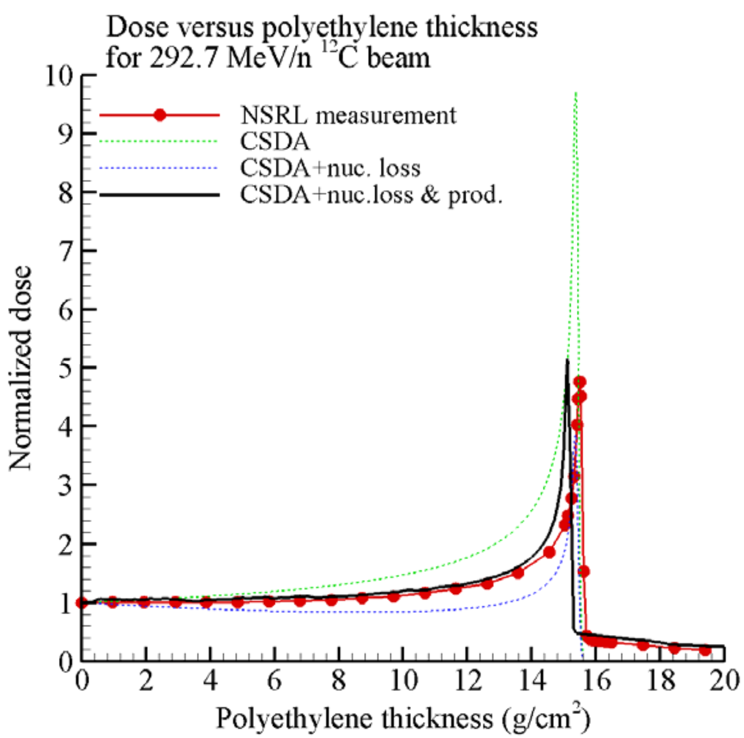
$$\frac{\partial}{\partial x}\phi_j(x,E) - \frac{\partial}{\partial E}[\phi_j(x,E)\tilde{S}_j(E)] + \sigma_j(E)\phi_j(x,E) = \sum_k \int \sigma_{k\to j}(E,E')\phi_k(x,E')\,dE'$$




- Reasonable agreement in plateau region
- "tail" of curve associated with nuclear fragments is represented
- Discrepancies in magnitude and location of Bragg peak are sensitive to beam-line setup, detector response, and higher order transport effects (3D, straggling, etc.) which are not accounted for here

# Space Radiation Transport Methods

- Radiation transport methods can be generally classified into two main categories
  - Deterministic: develop and solve the relevant transport equations using analytical and numerical methods
  - Monte Carlo: use random-number generators to sample the reaction probabilities (cross sections) and track each particle history

- For space applications, it has been recognized for some time that Monte Carlo methods are computationally restrictive
  - For example: Recent simulations with just GCR protons in simplified spherical geometry with two materials required <u>several CPU years</u> to complete

- Monte Carlo codes used in space applications
  - PHITS, Geant4, FLUKA, MCNP6, HETC-HEDS, SHIELD
  - These codes are "general purpose", so they are also sometimes used in treatment planning, nuclear reactor design, accelerator design, and high energy physics experiments

- Deterministic codes used in space applications
  - HZETRN
  - Not a "general purpose" code: developed specifically for space applications with some applicability in beam-line comparisons for validation

# Deterministic Methods

- ~40 years ago, Wilson et al. (NASA LaRC) began investigating deterministic methods for space radiation transport applications
  - Starting point was the 3D linear Boltzmann transport equation
  - Among other simplifications, the straight ahead approximation was used to reduce the problem to 1D
  - This formed the basis for the original versions of HZETRN

- Linear Boltzmann transport equation (3D):
  - x is position vector and Ω is direction vector

$$\left[\Omega \bullet \nabla - \frac{\partial}{\partial E}\tilde{S}_j(E) + \sigma_j(E)\right]\phi_j(x,E,\Omega) = \sum_k \int \sigma_{k\rightarrow j}(E,E',\Omega,\Omega')\phi_k(x,E',\Omega')\,dE'\,d\Omega'$$

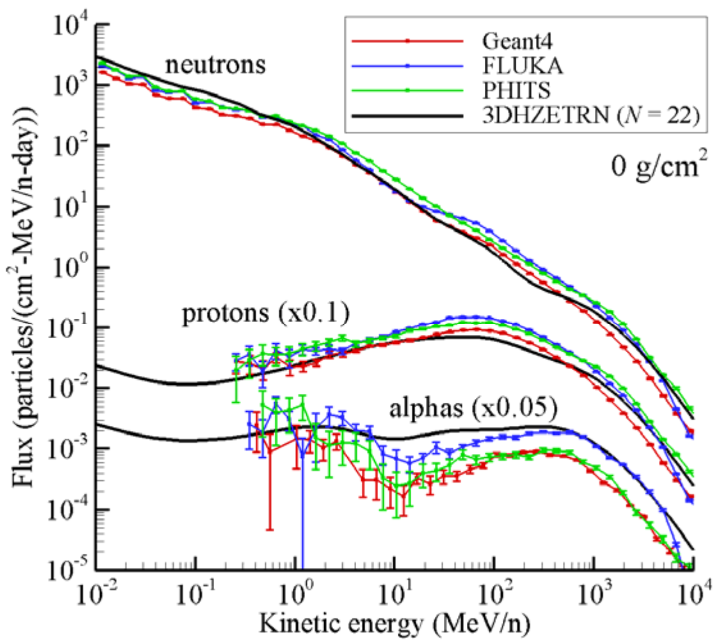
- Linear Boltzmann transport equation (1D):
  - x is scalar depth in material

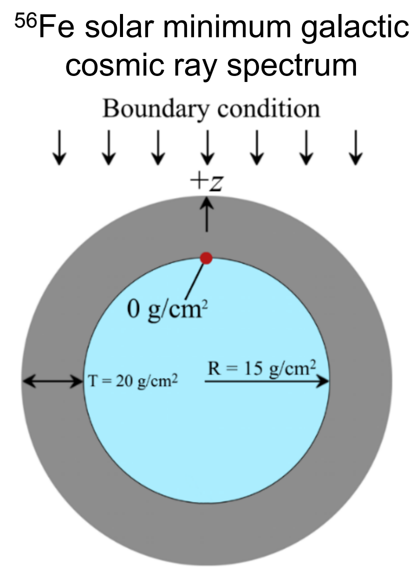
$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E}\tilde{S}_j(E) + \sigma_j(E)\right]\phi_j(x,E) = \sum_k \int \sigma_{k\rightarrow j}(E,E')\phi_k(x,E')\,dE'$$

# Deterministic Methods

- HZETRN has been widely used for space applications over the past several decades
  - Run times are on the order of seconds to minutes on a single CPU for most calculations
  - Extensively verified against Monte Carlo codes and validated against space flight data
  - Due to the computational efficiency, the HZETRN code is used in research, vehicle design, mission planning, and astronaut risk assessment

- Recent efforts in transport code development have implemented 3D corrections into HZETRN for neutrons and light ions
  - Overall computational efficiency has been maintained
  - Improved agreement with fully 3D Monte Carlo codes in various shielding geometries

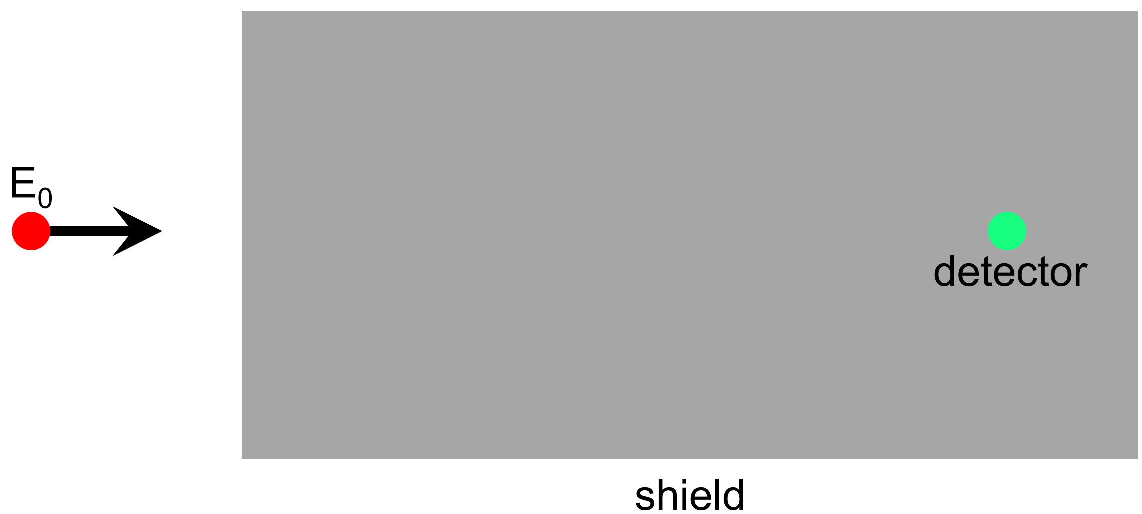



Tissue sphere with radius 15 g/cm$^2$ surrounded by 20 g/cm$^2$ of aluminum

# Monte Carlo Methods

- Simplified Monte Carlo transport procedure is described below
  - Consider a single particle (red dot) with a known direction and kinetic energy
  - The direction is indicated by the arrow, and the energy is denoted as $E_0$



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  - Consider a single particle (red dot) with a known direction and kinetic energy
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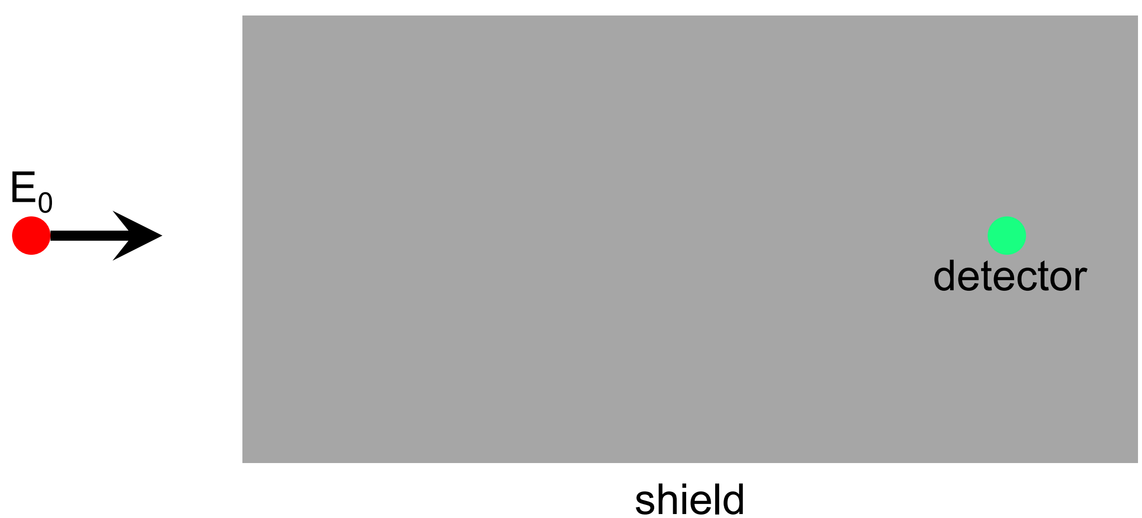
  - Draw a random number and sample the interaction probabilities to determine step length
    - Kind of like asking: “How far will the particle go before having a nuclear interaction?”



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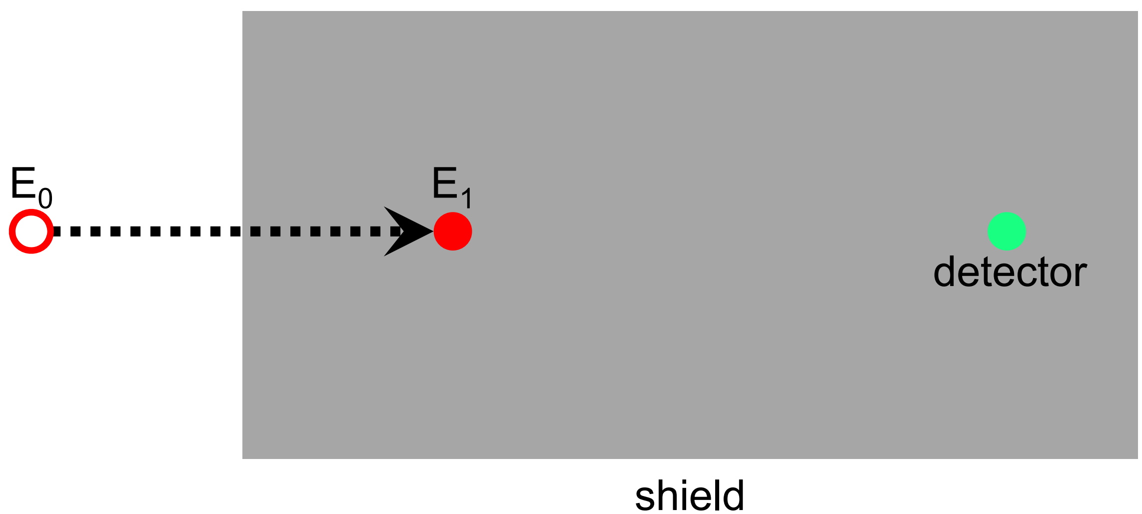

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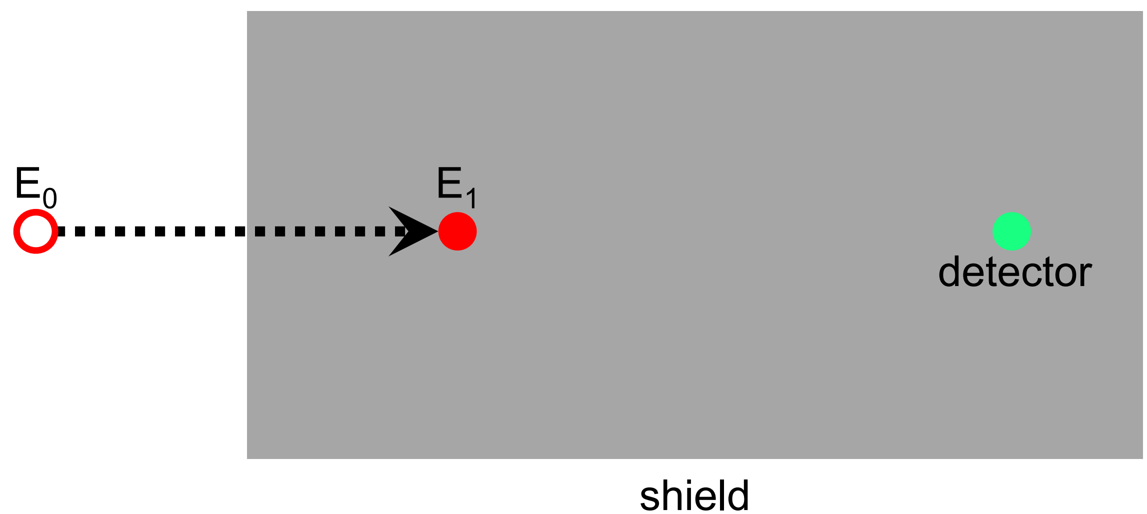
  - Along the step, assume energy is lost due to atomic interactions according to the CSDA
    - The energy at the end of the step ($E_1$) can be precisely calculated



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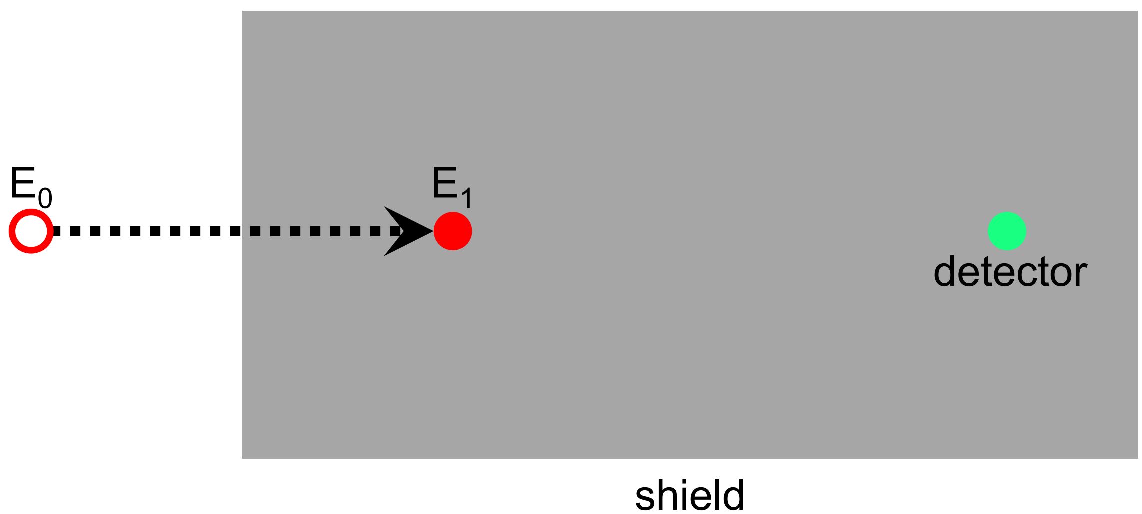
  - The direction is indicated by the arrow, and the energy is denoted as $E_0$
  - Draw a random number and sample the interaction probabilities to determine what type of nuclear interaction occurs (elastic or inelastic)
    - For this example, assume an elastic collision occurred
    - Draw another random number and sample elastic cross sections to determine new energy ($E_2$) and direction



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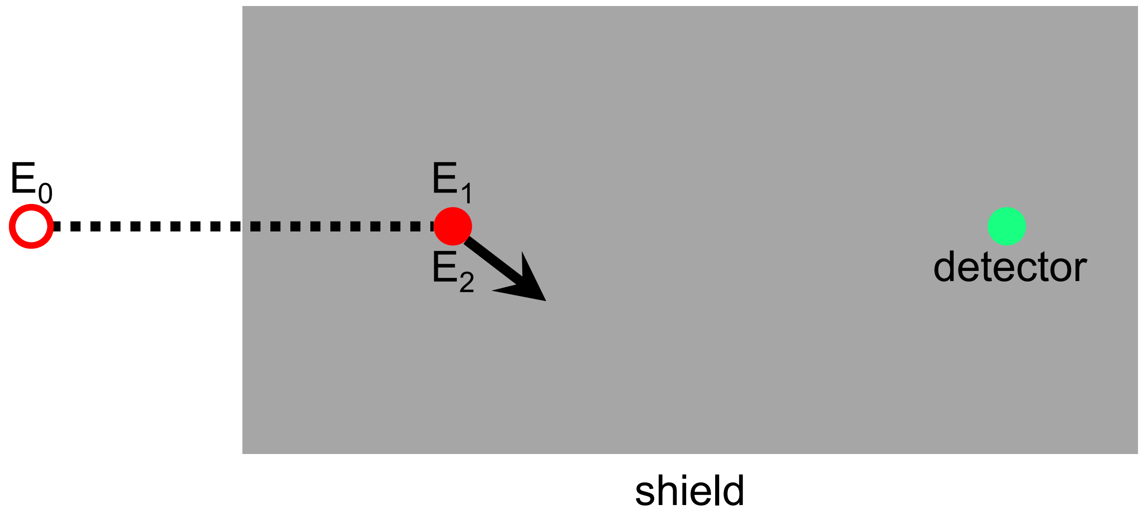

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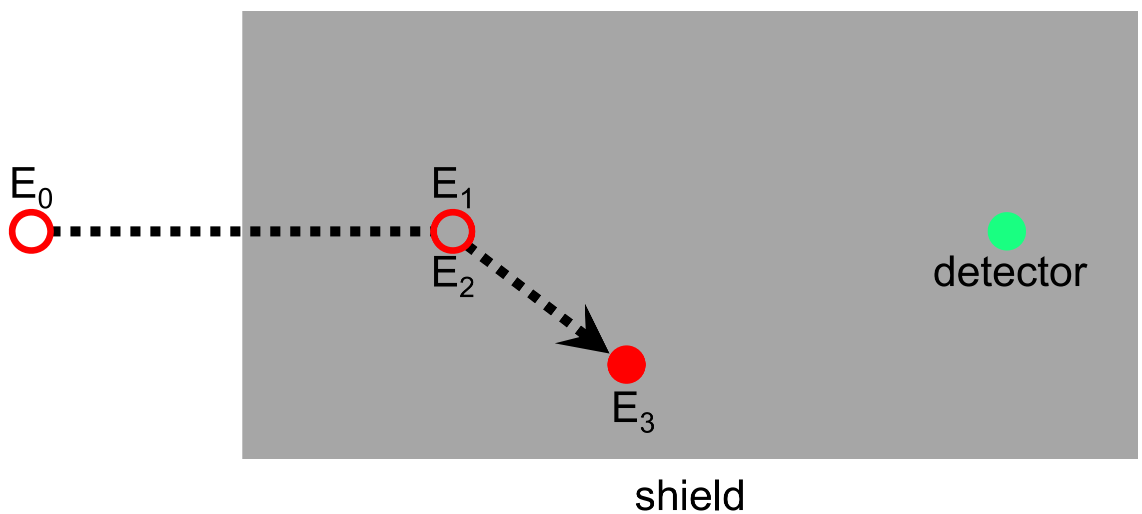

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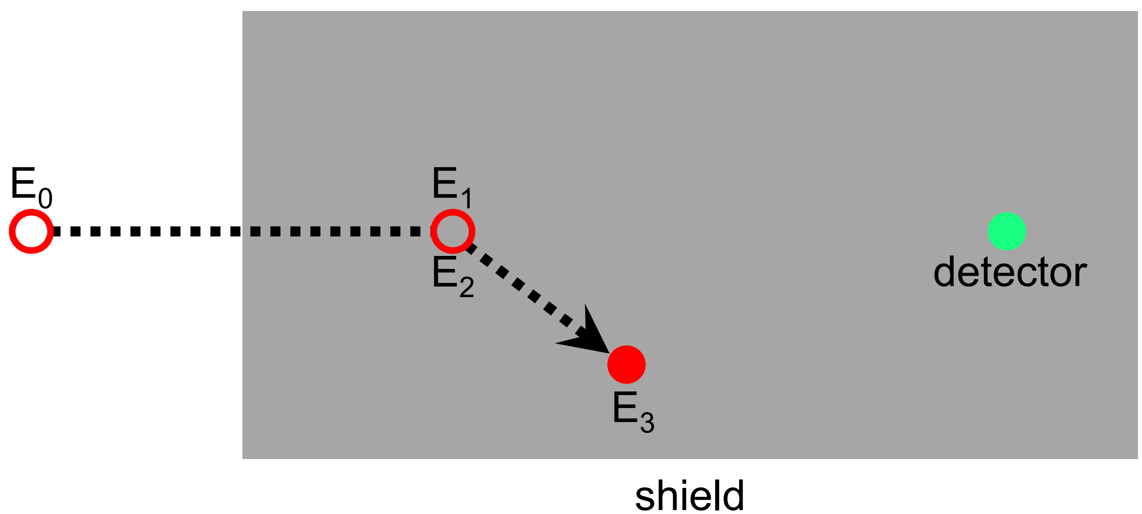
  - Along the step, assume energy is lost due to atomic interactions according to the CSDA
    - The energy at the end of the step ($E_3$) can be precisely calculated



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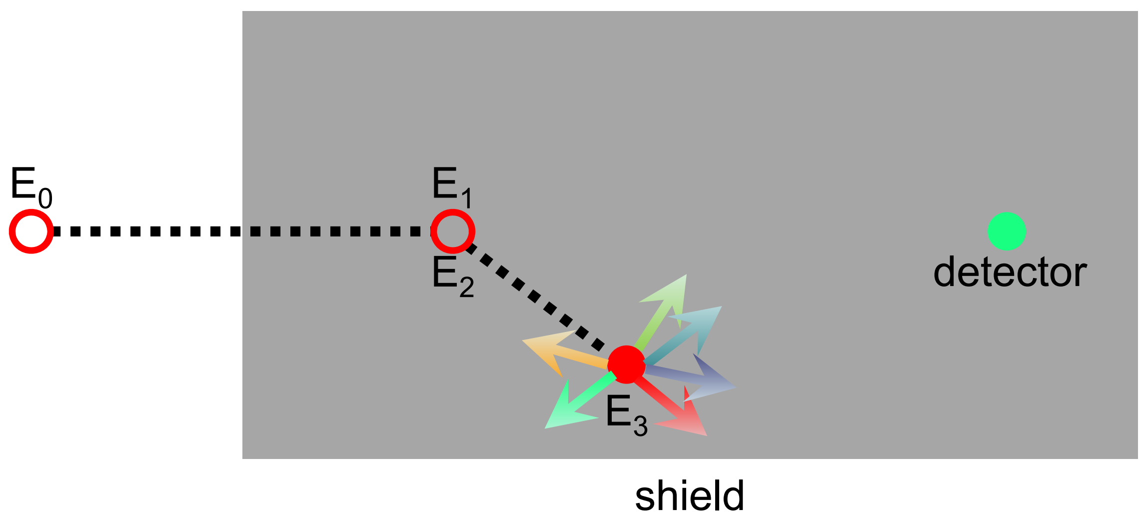
  - Draw a random number and sample the interaction probabilities to determine what type of nuclear interaction occurs (elastic or inelastic)
    - For this example, assume an <u>inelastic</u> collision occurred
    - Draw another “set” of random numbers to determine the types of particles produced, energies, and angles



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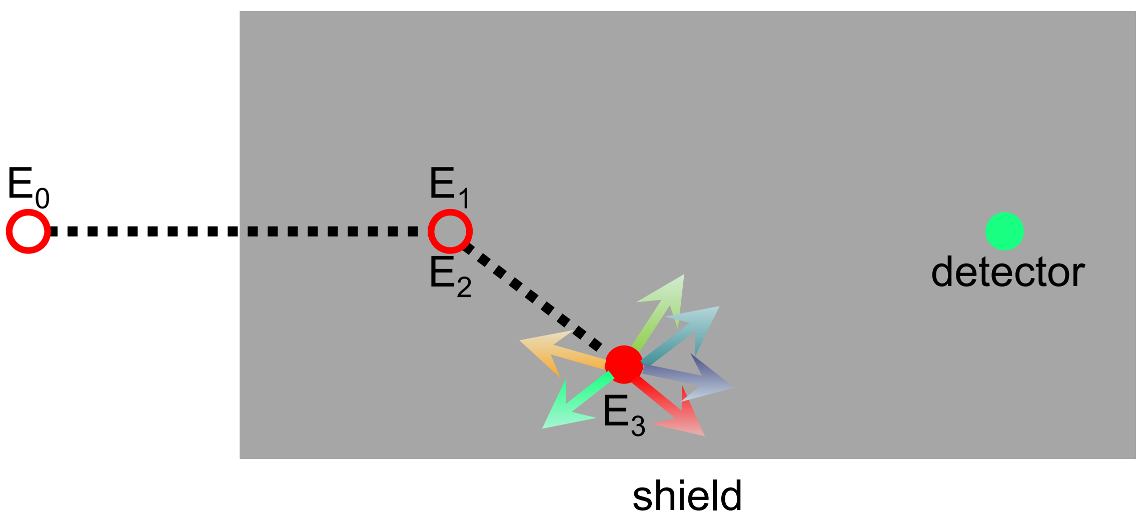
  - Repeat process for all produced particles
  - Continue with procedure until all particles have stopped or escaped from geometry
  - Then repeat again with a new particle at the boundary



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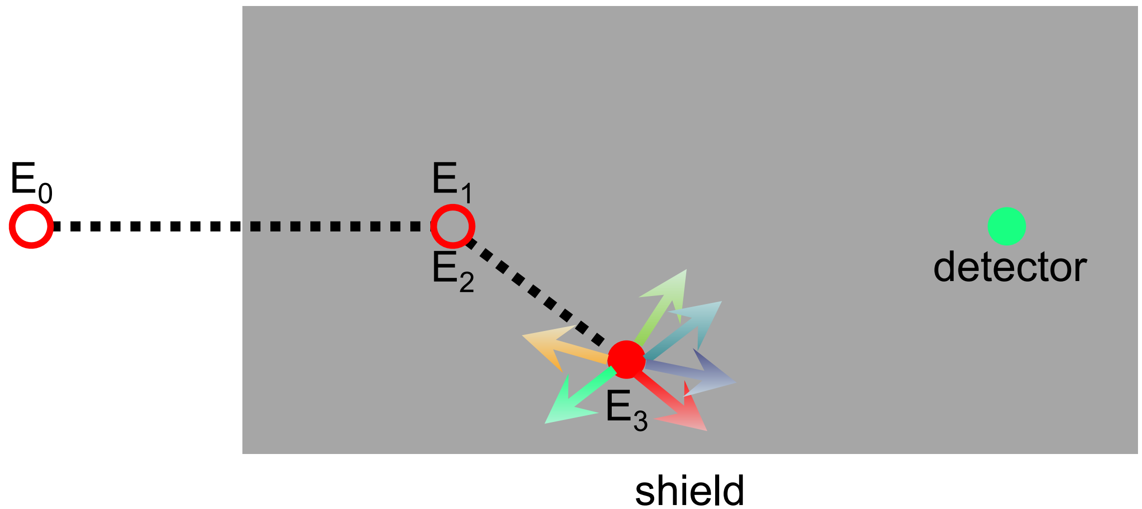
  - Process is repeated until detector has counted enough particles to achieve statistical convergence (Central Limit Theorem)
  - For space applications: Usually at least $10^6$ (up to $10^{11}$ or more) are needed depending on boundary condition, geometry, and detector



# Transport Methods: Recap

- There are two basic methods for space radiation transport
  - Monte Carlo (Geant4, FLUKA, PHITS, MCNP6, HETC-HEDS, SHIELD)
  - Deterministic (HZETRN)

- Monte Carlo: Use random number generators to sample physical interactions and individually track each particle

- Deterministic: Use analytical and numerical methods to solve the Boltzmann transport equation

- For space applications
  - Monte Carlo methods are difficult to implement in early design and planning phases due to computational cost (long run times)
  - Paradigm has been to use Monte Carlo near the end of design cycle when more detailed vehicle model is available to verify deterministic code analysis and results
  - Deterministic methods (HZETRN) are rapid and therefore easier to use when vehicle might only be represented as simple geometries like spheres or cylinders
  - In many comparisons, HZETRN agrees with Monte Carlo to the extent they agree with each other
  - Both methods provide valuable tools that are used in various applications

# Design Tools

- The HZETRN transport code and other models used at NASA to support mission planning and vehicle design have been integrated into a web-based framework
  - OLTARIS: https://oltaris.nasa.gov


- Various galactic cosmic ray models
- Various solar particle event (SPE) options
  - Fits to historically significant events (i.e.1972, 1989) are available and can be scaled
  - User-defined spectra are supported through commonly used fitting functions with few parameters

- Environmental models can be evaluated in low Earth orbit, deep space, or on planetary surface

- Environmental models are integrated with physics/transport models, detailed human phantom models and various geometry options

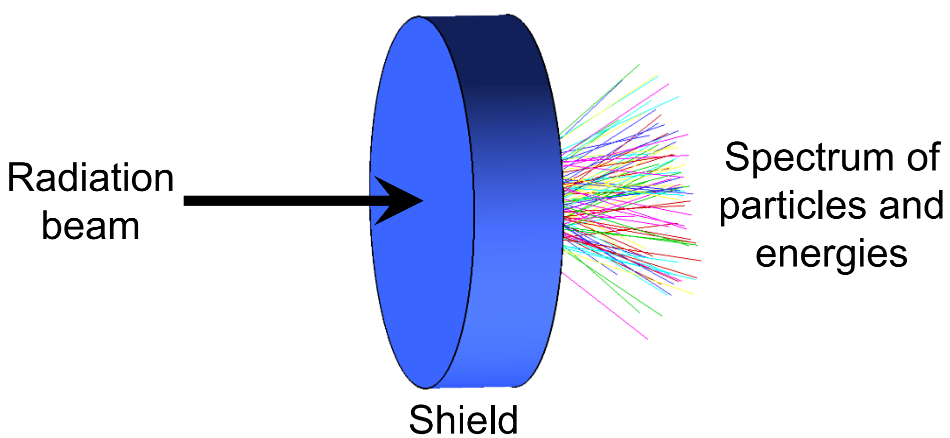
Differences between laboratory and space environments

# Space vs. Laboratory

- In a laboratory, the radiation environment being considered as input into a transport code is usually a mono-energetic ion beam
  - e.g. $^{56}Fe$ at 1 GeV/n

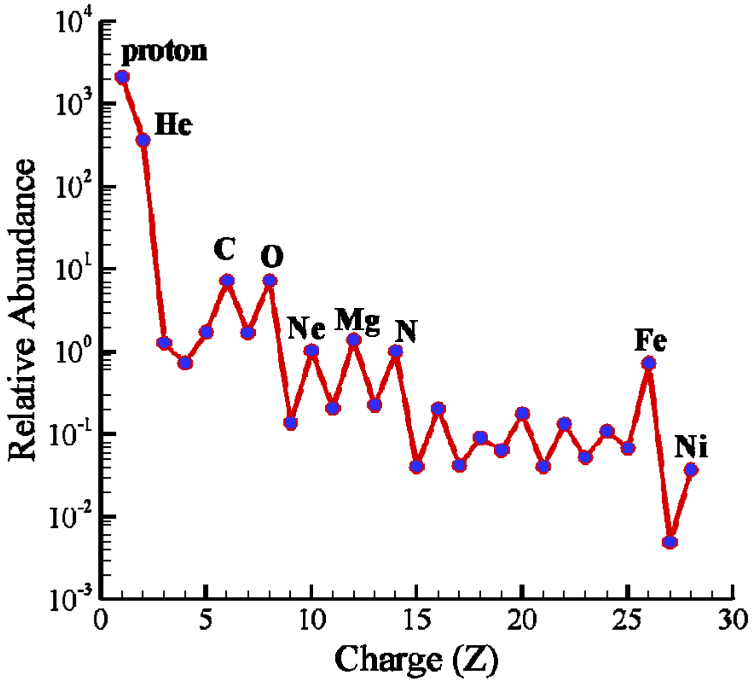
- In space, the radiation environment being considered as input into a transport code is broad spectrum of energies and particles
  - For GCR: All ions on the periodic table covering energies from MeV/n to GeV/n
  - For SPE: Mainly protons less than several GeV/n (very intense at lower energies)

- The complexity of the space environment, compared to a mono-energetic ion beam, provides characteristically different physical and biological results

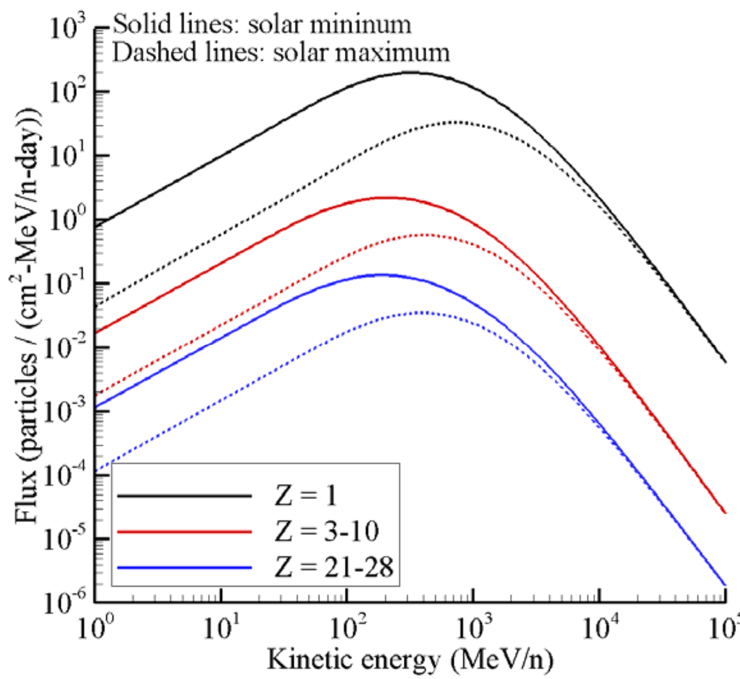


# Space Environment: GCR

- The galactic cosmic ray (GCR) environment is omnipresent in space and fluctuates between solar minimum and solar maximum on an approximate 11 year cycle
  - Exposures differ by approximately a factor of 2 between nominal solar extremes
  - Broad spectrum of particles (most of the periodic table) and energies (many orders of magnitude)
  - Difficult to shield against due to high energy and complexity of field



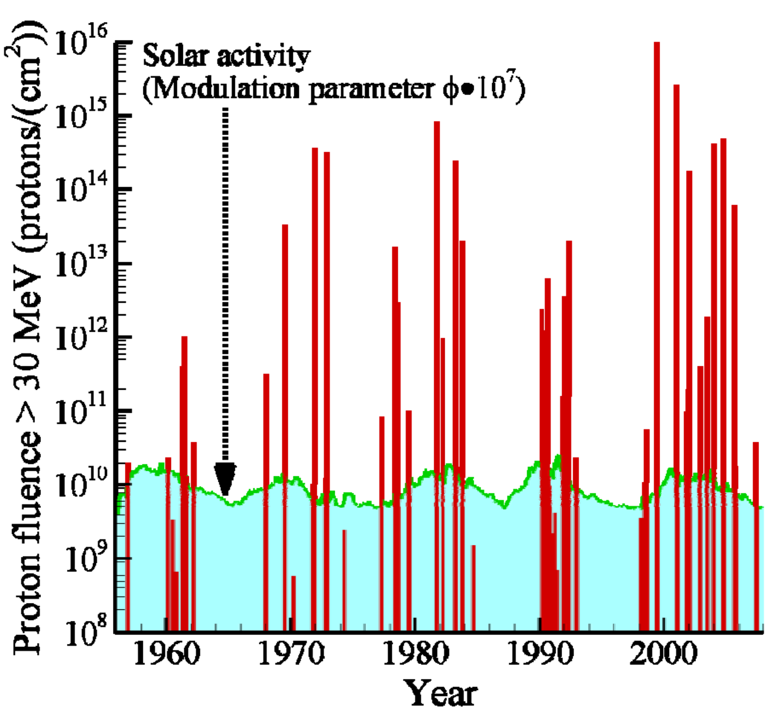

Relative abundance of elements in the 1977 solar minimum GCR environment, normalized to neon



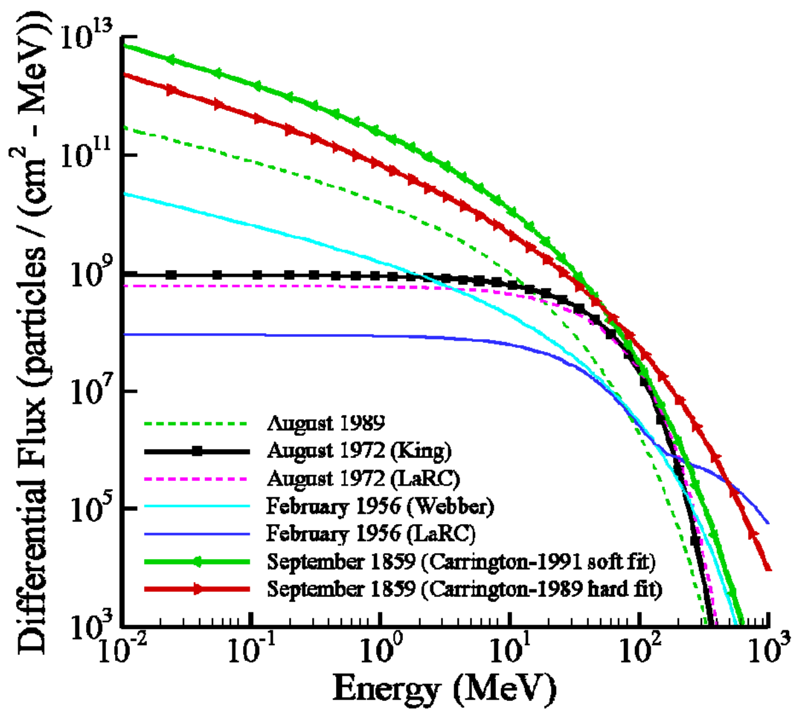

GCR flux at solar minimum and solar maximum

# Space Environment: SPE

- Solar particle events (SPE) are intense bursts of protons from the Sun
  - Associated with coronal mass ejections and solar flares
  - Difficult to predict occurrence, spectral shape, or magnitude
  - More likely to occur during periods of heightened solar activity (solar max)
  - Energies up to several hundred MeV (may extend up to GeV)
  - Presents serious acute risk to astronauts if not adequately shielded



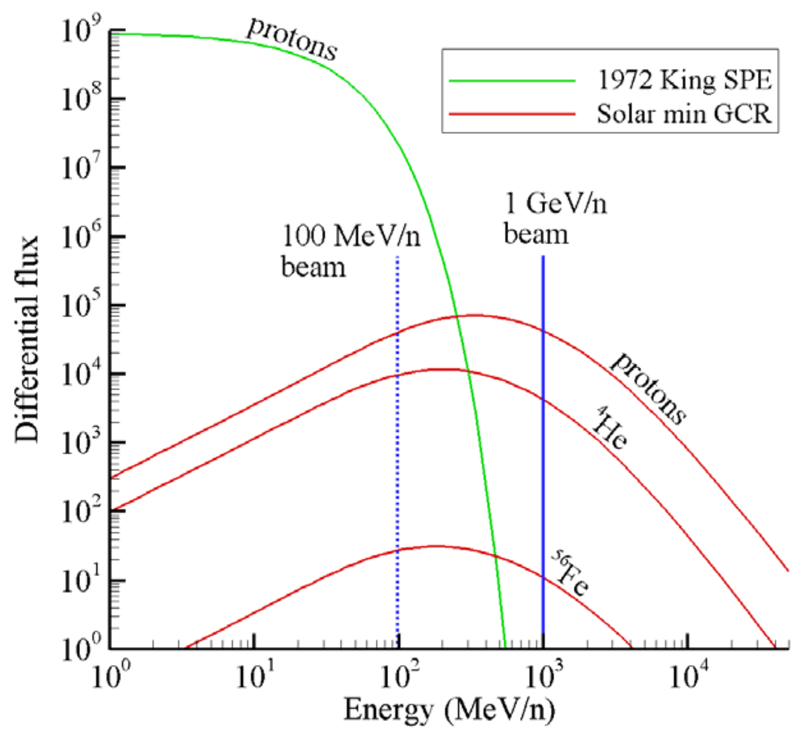

Integral proton fluence (E > 30 MeV) for SPEs from 1956 - 2007




Historical solar particle events

# Space vs. Laboratory

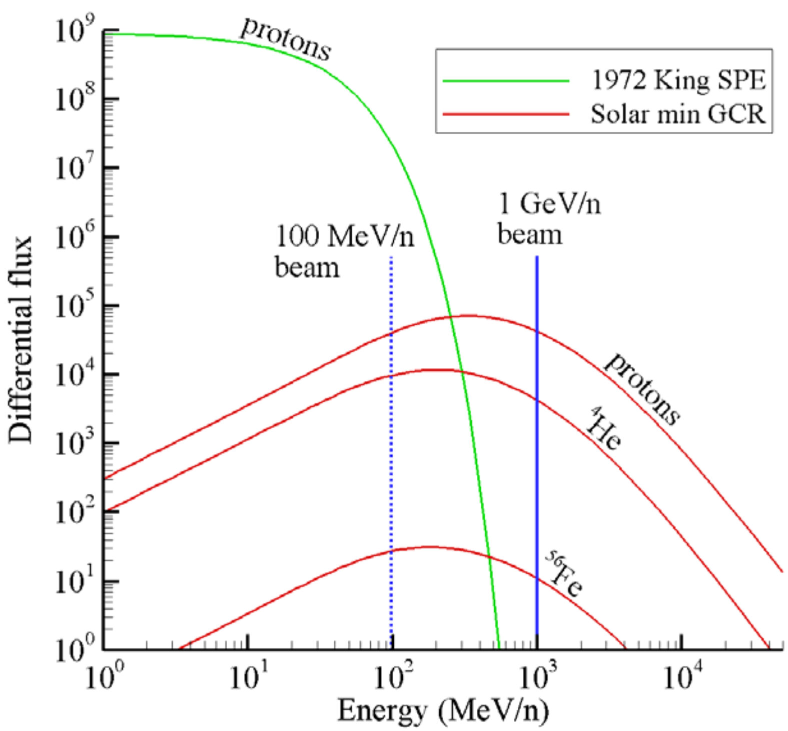
- Substantial differences between SPE, GCR, and beam energy spectra
  - GCR energies peak near 300 MeV/n and extend up to several hundred GeV/n
  - SPE energies fall off rapidly after 100 MeV for the 1972 event
  - Very intense (high flux) spectrum at lower energies for SPE
  - Example mono-energetic beam spectra are shown to provide some context



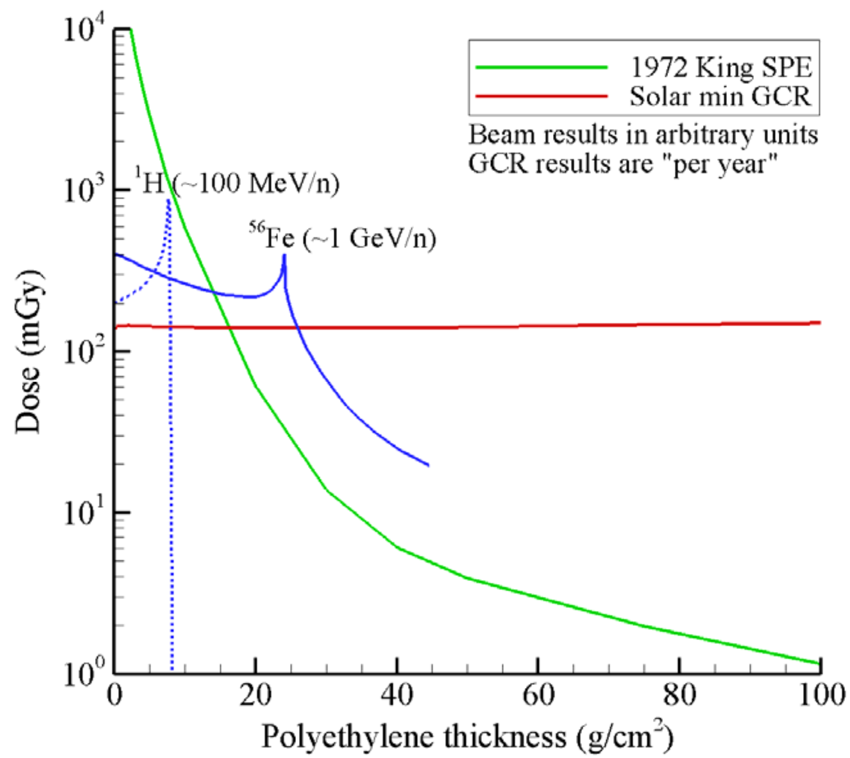

1972 King SPE proton spectra (particles/(cm$^2$-MeV-event)) and selected solar min GCR ion spectra (particles/(cm2-MeV/n-year)) plotted along with 100 MeV/n and 1 GeV/n beams

# Space vs. Laboratory

- Substantial differences between dose vs. depth results for various environments
  - SPE dose is very large with minimal shielding but falls off rapidly
  - GCR dose remains relatively flat as a function of polyethylene thickness
  - Beam doses show characteristic Bragg peaks dependent on ion charge and energy




1972 King SPE proton spectra (particles/(cm$^2$-MeV-event)) and selected solar min GCR ion spectra (particles/(cm2-MeV/n-year)) plotted along with 100 MeV/n and 1 GeV/n beams




Dose (mGy) versus polyethylene thickness for SPE, GCR and for mono-energetic ion beams (NSRL data)

# Summary

- Radiation transport describes the analytical and computational procedures that describe how radiation is modified as it passes through shielding and tissue
  - Atomic and nuclear interaction processes need to be represented
  - Atomic interactions provide “first order” solution for charged particle transport

- Radiation transport models can be broadly classified as either Monte Carlo or deterministic
  - Monte Carlo: Sample the interaction probabilities and track individual particle histories
  - Deterministic: Develop and solve the relevant transport equations using analytical and numerical methods

- For space applications, NASA has pursued deterministic methods, leading to highly efficient tools capable of supporting vehicle design, mission planning, and risk assessment
  - NASA’s space radiation transport code is HZETRN
  - HZETRN and related tools have been integrated into the OLTARIS website

- Transport codes are critical tools for describing transport of GCR, SPE, and mono-energetic beams through shielding materials and tissue
  - SPE: Dose is very large for thin shielding but falls off rapidly with increasing shield thickness
  - GCR: Dose is not effectively mitigated with shielding thickness
  - Beams: Dose vs. depth profile is highly dependent on ion species, energy, and shielding material (important to consider possible impact on radiobiology experiments, especially with animals)